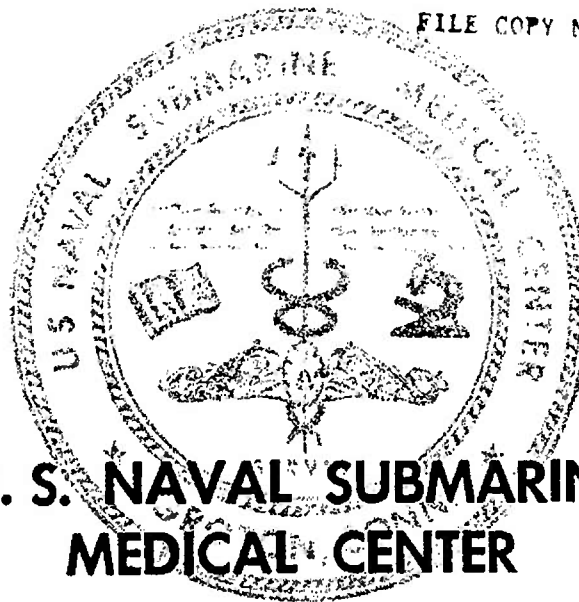


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REPORT NUMBER 503

THE VISIBILITY OF COLORS UNDERWATER

by

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and

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Bureau of Medicine and Surgery, Navy Department
Research Work Unit MF022.01.04-9005.01

Approved and Released by:

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Naval Submarine Medical Center

23 October 1967

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SUMMARY PAGE

THE PROBLEM

To determine: (1) the most and least visible colors for use underwater; and (2) whether these results are applicable in all bodies of water.

FINDINGS

The specific colors which were most visible varied with the type of water investigated, from orange in murky water to blue-green in clear water. Fluorescent paints were always superior to non-fluorescent of the same color and white was the best non-fluorescent. Gray and black were the most difficult to see.

APPLICATIONS

Specific colors are recommended as aids to visibility for use in underwater operations of divers and operators of small submersibles. Other colors are recommended for concealment and combinations are chosen for cases in which color confusions underwater must be avoided.

ADMINISTRATIVE INFORMATION

This investigation was conducted as a part of Bureau of Medicine and Surgery Work Unit MF022.01.04-9005 - Procedures for Improving Vision, Auditory Communication, and Orientation Underwater. The manuscript was approved on 8 December 1966 and submitted to the Journal of the Optical Society of America. It was subsequently published in that journal, Vol. 57, No. 6, 802-809, June 1967. This reprint has been designated as Report No. 1 on the Work Unit listed above, and as SubMedResLab, SubMedCen Report No. 503 under date of 23 October 1967.

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Visibility of Colors Underwater*

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(Received 5 January 1967)

The underwater visibility of various colors, both fluorescent and nonfluorescent, was measured in four different bodies of water. The waters were selected to sample the continuum from very murky to clear. SCUBA divers observed with a horizontal path and other subjects on the surface looked down vertically. Fluorescent colors were always more visible than nonfluorescent, but the specific colors that were easiest and most difficult to see depended upon the body of water.

INDEX HEADINGS: Vision; Color; Oceanography.

THE increasing penetration of man into the sea has raised acute problems of visibility underwater. In some cases, the turbidity of the water is so severe that no visual signal can be used to assure the diver's return to his base of operations. At the other extreme, there are reported instances of divers seeing clearly for 200 ft in all directions. Between these two extremes lies the wide range of waters in which divers and small submersibles work and for which aids to visibility are possible.

The use of colored paints on objects is an obvious means of changing their visibility either by enhancing their contrast with the surround or by camouflaging them to merge with their background. The problem of determining which colors will be most and least visible underwater is, however, much more complicated than it is in air. Transmission of light through air does not appreciably change its spectral composition, but transmission through water can alter the distribution beyond recognition. Furthermore, both the quantity and quality of the change depend on the particular body of water involved.

Water selectively absorbs light of different wavelengths. Pure water has its greatest transmittance at 480 m μ in the blue-green region of the spectrum. Many natural contaminants of pure water, such as plankton, not only lower the total transmittance but selectively

absorb more of the short- than of the long-wavelengths. The peak of the transmittance curve is thus moved from 480 m μ toward the longer wavelengths as the water becomes less clear. Similarly, as we move from open ocean toward the coast, the source of silt and pollution, the peak is moved further into the yellow-green and even yellow portions of the spectrum.¹ Thus, the relative visibility of paints of different colors can be expected to vary considerably with the body of water in which they are immersed. One of the most effective means of increasing visibility in air is the use of fluorescent paints, as evidenced by the expanding use of these paints in traffic signals, on aircraft, and for hunters' clothing. The advantage, of course, is the increased brightness and color contrast produced when energy of short wavelengths is converted to longer wavelengths to which the eye is more sensitive.² Thus reflectances higher than those of natural objects and often effectively in excess of 100% are possible as are high saturations similar to those of monochromatic light. The most effective colors in air are varieties of orange, which combine the advantages of great energy conversion, high sensitivity of the human eye, and good color contrast with natural backgrounds, which are often blue or green.

* From Bureau of Medicine and Surgery, Navy Department, Research Work Unit MF011.99-9002. The opinions or assertions contained herein are the private ones of the authors and are not to be construed as official or reflecting the views of the Navy Department or the Naval Service at large.

¹ R. H. Oster and G. L. Clarke, *J. Opt. Soc. Am.* 25, 84 (1935); E. O. Hulburt, *J. Opt. Soc. Am.* 13, 553 (1926); 35, 698 (1945); N. G. Jerlov, *Reports of the Swedish Deep-Sea Expedition of 1947-48* (1951), Vol. III; H. V. Sverdrup, M. W. Johnson, and R. H. Fleming, *The Oceans* (Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1942), pp. 84-86, 776, 783.

² R. W. Voedisch, *Am. Paint J.*, 7 Aug. 1961.

Most of these advantages are retained in water, and theoretically the use of fluorescent paint is a promising means of improving underwater visibility. Since the energy required for excitation is primarily in the violet, blue, and green portions of the spectrum, sufficient energy should be available at great depths in clear water.

This study is an empirical determination of the relative visibility underwater of paints of various colors, both fluorescent and nonfluorescent, in different bodies of water.

APPARATUS AND PROCEDURE

Fourteen paints were tested for underwater visibility; they were a blue, green, yellow, orange, and red in both fluorescent and nonfluorescent varieties plus white, gray, and black. Their characteristics are listed in Table I. Since fluorescent orange has been so effective

TABLE I. Specifications of paint samples.

Sample No.	Color	Luminance factor %T	CIE chromaticity coordinates x	y	z
FLUORESCENT					
1	Blue	20.3	0.1591	0.1756	0.6653
3	Green	60.4	0.2625	0.6005	0.1370
5	Yellow-Green	111.2	0.4138	0.5472	0.0392
7	Yellow-Orange	95.4	0.5558	0.4183	0.0258
9	Orange	70.4	0.6065	0.3853	0.0082
11	Red-Orange	49.2	0.6323	0.3364	0.0313
NONFLUORESCENT					
2	Blue	12.8	0.2199	0.2085	0.5715
4	Green	12.3	0.2755	0.5183	0.2063
6	Yellow	44.4	0.5052	0.4548	0.0401
8	Orange	16.6	0.6024	0.3535	0.0441
10	Red	9.0	0.6024	0.3047	0.0929
12	White	81.5	0.3080	0.3188	0.3732
13	Grey	13.6	0.3197	0.3325	0.3477
14	Black	3.7	0.3058	0.3209	0.3833

in air, a number of hues are available and several were included. Paints were chosen to be representative of commercially available items and varied in reflectance as well as hue.

The paints were applied to spherical aluminum floats, 20 cm in diameter. Holes were drilled in each float and they were filled with sufficient water to reduce them to very slight positive buoyancy. The floats were submerged, one or two at a time, either from the surface by use of a pulley system or by a SCUBA diver on the bottom operating an anchor and snap-hook system. Viewing was done either on a horizontal path by SCUBA divers or on a vertical path from the surface. In each case the target was viewed against the natural water background.

Comparative visibility of the various colored spheres was generally assessed by a color-naming technique. Spheres were presented, singly, in a random order, and the subject was asked to name the color he saw. The distance between the subject and the ball was

between that at which all of the colors could be perceived clearly and that at which none could be seen. This distance is referred to as the threshold or limit of visibility.

In addition to color naming, brightness comparisons between several combinations of two spheres were made to assess which, among the several most visible colors, was easiest to see.

For the vertical line of sight from the surface, data were obtained by color naming, as described above, and also by moving the sphere up from a depth at which it was not visible to the distance from the surface at which the color could be correctly identified.

Natural illumination was used throughout the experiment. Since each day's data consisted of relative comparisons among the various colors, no attempt was made to control the absolute illumination conditions. Instead, differences of absolute energy levels (caused for example, by a rainy vs sunny day) were compensated for by changing the subject's viewing distance for the day. While there are some variations of the spectral distribution of natural daylight due to atmospheric conditions, these should be minor compared to the selectivity of the water. This assumption was confirmed empirically by comparing runs on rainy and sunny days at the same location. Within the relative comparison of a single run, however, care was taken to exclude changing conditions which would affect visibility, such as variable cloud cover. (One run had to be omitted owing to visibility variations caused by intermittent schools of fish.)

Subjects for horizontal viewing were SCUBA divers attached to the Military Operations Branch of NSMC and to the Naval Mine Defense Laboratory in Panama City, Florida. For vertical viewing both divers and civilian members of the Vision Branch of NSMC were utilized. All subjects had normal color vision.

TYPES OF WATER INVESTIGATED

The same experiment was repeated in four different bodies of water, which were chosen to sample the continuum from very murky to clear. Water samples were taken, spectral transmittance was measured with a Beckman spectrophotometer; the data are summarized in Table II. The over-all transmittance of visible light by one meter of water varies from 5% for the Thames River to 91.5% for the fresh water in Morrison Springs. In addition to this sizable difference of over-all transmittance, the color of the water also varies, owing to quite different spectral transmittance characteristics of the samples.

Both of these points are illustrated in Fig. 1 which shows the transmittance of 1 m of the various waters as a function of the wavelength of light. The curve for Morrison Springs is the same as distilled water and has a maximum transmittance of over 90% at 480 m μ . The only difference between the samples from the Spring

TABLE II. Characteristics of various bodies of water investigated.

Body of water	Description	Transmittance of sunlight by 1 m of water	α
Thames River near Sub Base	extremely murky, polluted	0.05	2.3
Long Island Sound in Fort Pond Bay	moderately turbid	0.50	0.7
Gulf of Mexico off Panama City	clear	0.90	0.1
Morrison Springs fresh water	famous for clarity	0.92	0.09

and the Gulf of Mexico is a lower transmittance in the violet and blue portions, presumably due mainly to plankton. The Long Island Sound water shows less transmittance throughout the spectrum, with the greatest loss in the blue and blue-green portions. In the Thames River, very little light is transmitted at all and the shape of the curve has been completely transformed, with the greatest transmittance in the long wavelengths.

The difference among the spectral transmittance curves depicted thus far are for only 1 m of water; they become even more exaggerated when calculated for the actual viewing distances used in the experiment. Since transmittance is related to viewing distance by

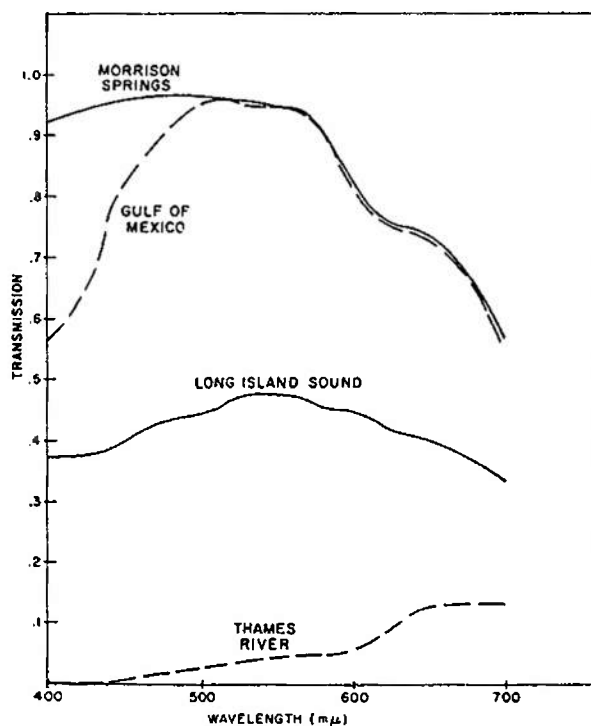


FIG. 1. Spectral transmittance of 1 m of various bodies of water.

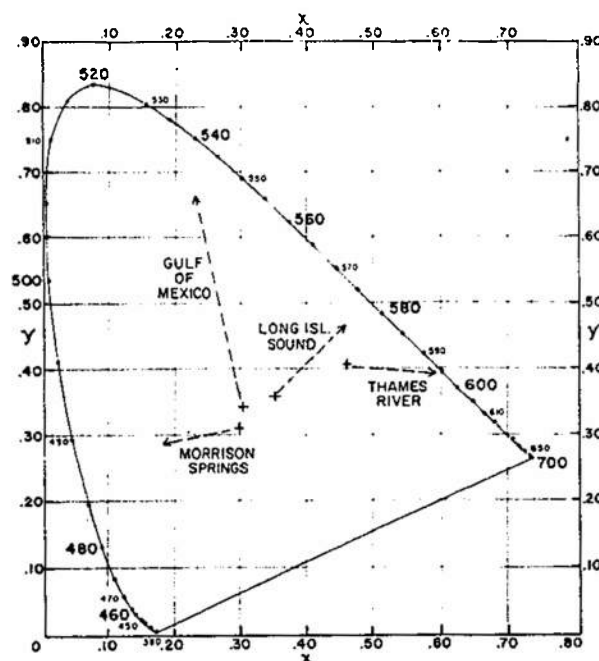


FIG. 2. Chromaticity values of 1 m of water compared with values calculated for distances actually used in experiment.

a power function, the wavelength selection becomes extreme as the distance the light travels through the water increases.

Spectral transmittance curves have been calculated for the appropriate observing distances. The changes of the distributions are shown in the CIE diagram of Fig. 2. The tail of the arrow refers to the appearance of natural daylight through 1 m of the water sample; the head of the arrow shows the appearance through the

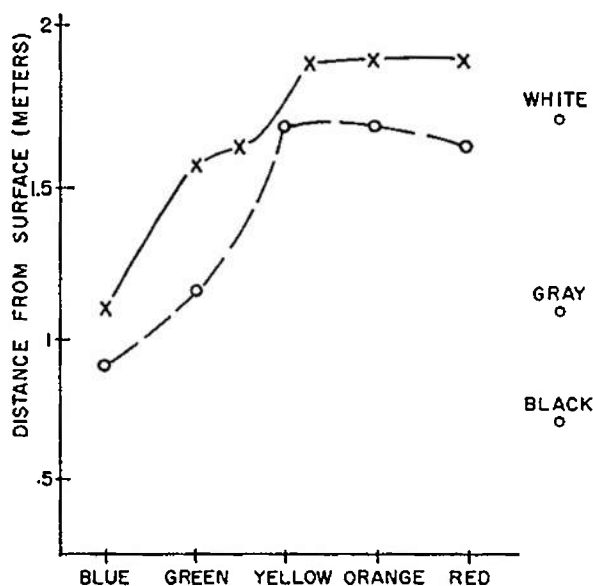


FIG. 3. Visibility of various colors in Thames River, Connecticut. Vertical viewing path, 15 subjects, fluorescent spheres —, nonfluorescent ----.

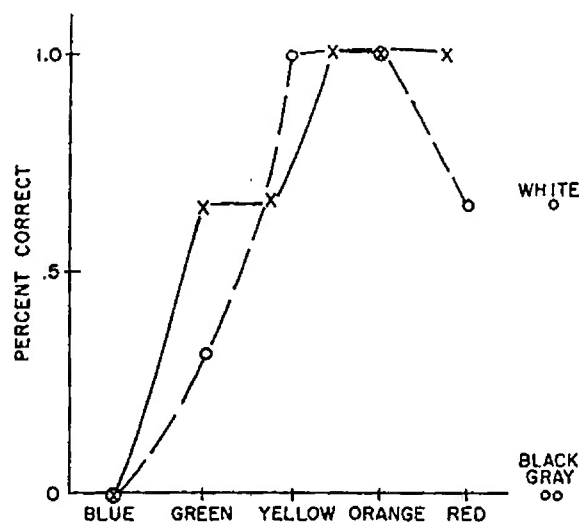


FIG. 4. Visibility of various colors in Thames River, Connecticut. Horizontal viewing path, 3 divers, depth 1.5 m, distance 1.8 m, fluorescent spheres —, nonfluorescent ----.

distance that was actually used in each viewing situation. Thus, natural daylight becomes yellow-orange after filtering with 1.8 m of Thames River water, yellow-green with 7 m of Long Island Sound water, green through 34 m of Gulf water, and blue-green through 30 m of Morrison Springs water.

RESULTS

A. Visibility

Figures 3-9 present the data obtained in the different bodies of water. In each case, some measure of the visibility of the color is plotted as a function of the color. For the vertical or surface viewing condition, the visibility measure is the depth of the target when it was first seen. For the horizontal viewing condition,

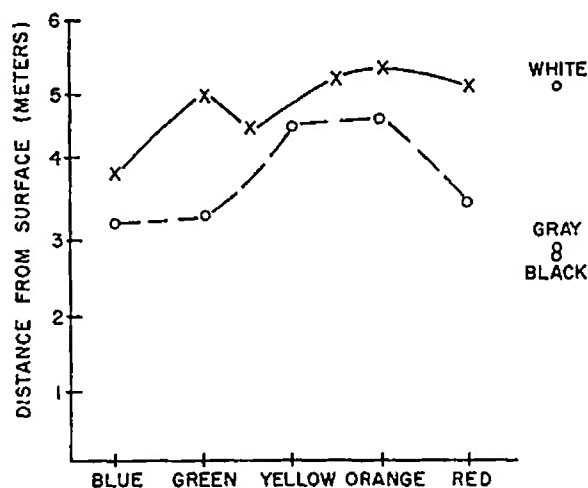


FIG. 5. Visibility of colors in Long Island Sound. Vertical viewing path, 5 subjects, fluorescent spheres —, nonfluorescent ----.

the measure is the proportion of correct responses obtained at a given distance from the target. Fluorescent and nonfluorescent colors are plotted separately in each figure, according to their dominant hue or hues on an arbitrarily spaced scale. (For example, yellow-green is plotted halfway between yellow and green.)

Comparison of the various figures shows that visibility varies tremendously with the body of water, from 1.5 to 1.8 m in Thames River to 26 m in Morrison Springs. Furthermore, the colors found to be most and least visible are quite different in the different waters. Also, except for a few minor inversions, fluorescent paints are much more visible than non-fluorescent of the same color.

Specific results for each body are listed below:

Thames River

(1) The colors of highest visibility are: for the fluorescent paints, the oranges (yellow-orange, orange,

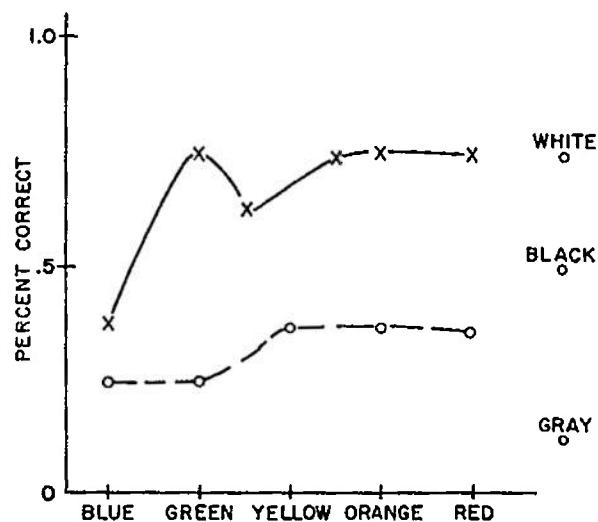


FIG. 6. Visibility of colors in Long Island Sound. Horizontal viewing path, 8 divers, depth 3.7 m, distance 3.4 m, fluorescent —, nonfluorescent ----.

and red-orange); for the nonfluorescent, white, yellow and orange.

(2) The most difficult colors to see are black, gray, blue, and green.

Long Island Sound

(1) The most visible fluorescent colors are the oranges and fluorescent green. White and nonfluorescent yellow and orange are also readily seen.

(2) Lowest visibility scores are found for gray, blue, green, and black. Over-all differences among colors are smaller than in the other three bodies of water.

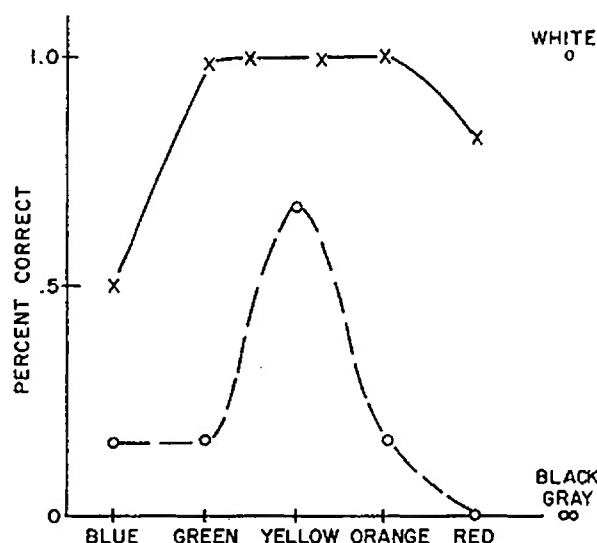


FIG. 7. Visibility of colors in Gulf of Mexico. Horizontal viewing path, 6 divers, depth 8.6 m, distance 11 m, fluorescent spheres —, nonfluorescent ----.

Gulf of Mexico

(1) Fluorescent greens or yellow-oranges are the easiest to see, green at the longer distances and yellow-orange at the shortest. White is the best of the non-fluorescent colors, followed by yellow and finally green at the longer distances.

(2) Nonfluorescent red and orange join gray and black for the first time as the most difficult to see.

Morrison Springs

(1) Distinct differences among colors are found; the two fluorescent greens and white are highly visible, while all others are relatively poor.

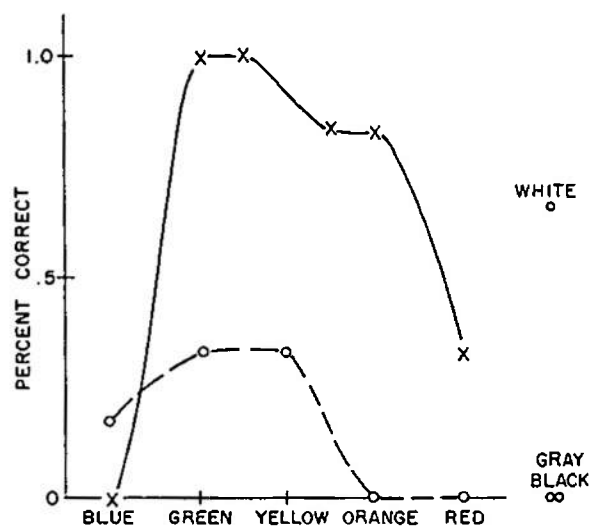


FIG. 8. Visibility of colors in Gulf of Mexico. Horizontal viewing path, 6 divers, depth 18 m, distance 16 m, fluorescent spheres —, nonfluorescent ----.

(2) Black, gray, red, orange, and two of the fluorescent oranges were not seen at all. Blue, for the first time, is one of the easiest colors rather than the most difficult to perceive.

B. Comparative Brightness

The results of the comparative brightness measures were essentially the same as the visibility measures. In the Thames, simultaneous brightness comparisons revealed the three fluorescent oranges to be approximately equal to each other and considerably brighter in appearance than any other color. The judgments of the brightest colors gradually shifted toward the shorter wavelengths in clearer water until, at Morrison Springs, all subjects agreed that both fluorescent greens were much brighter than any of the oranges, and that fluorescent yellow-orange was much brighter than fluorescent orange.

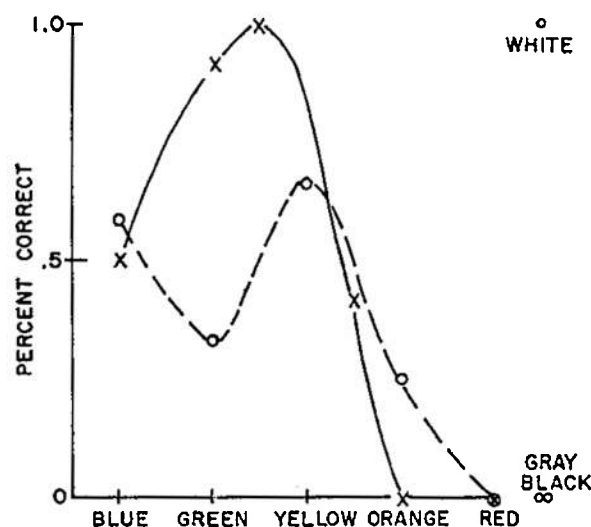


FIG. 9. Visibility of colors in Morrison Springs. Horizontal viewing path, 6 divers, depth 3.7 m, distance 26 m, fluorescent spheres —, nonfluorescent ----.

C. Color Confusions

The data presented thus far have dealt with the colors that are easiest to see at distances near the outer limit of visibility. They answer the question of what color to paint an object, if the problem is simply to make it as visible or invisible as possible.

The question of which colors to use for color coding, or absolute identification of colors, is quite different but may be equally important in underwater salvage work. The data in Table III give answers to this question by listing the color names in order of frequency given to the various targets in the various bodies of water.

Certain very systematic changes take place. In water that transmits more of the long wavelengths than of short, e.g., the Thames, the perceived colors change

TABLE III. Color names given the targets in order of frequency in various bodies of water.

Color in air	Thames River	Long Island Sound	Gulf of Mexico	Morrison Springs
FLUORESCENT				
Blue	Green Green-blue	Blue Green	Blue	Blue
Green	Green	Green Blue Yellow	Green Yellow	Yellow Green
Yellow-Green	Gray White Yellow	Yellow Green White	Yellow Green White	Yellow Green White
Yellow-Orange	Orange Red	Orange	Orange	Orange Yellow
Orange	Orange Red	Orange Red	Orange Red	Orange
Red-Orange	Red Orange	Orange Red	Orange Red	...
NONFLUORESCENT				
Blue	Gray Green Blue	Blue	Blue	Blue
Green	Green	Green Gray	Green Blue	Green
Yellow	Yellow Orange	Yellow Orange	Yellow	...
Orange	Red Orange	Orange	...	Orange Yellow
Red	Red Red-Orange	Orange Red	Black	Black
White	White Yellow	Green White Yellow	White Green Blue	White Blue
Gray	Gray	Green Black	Blue	...
Black	Black	Black

toward the longer wavelengths. Blue thus is rarely reported as blue but rather green; yellow is seen as orange, orange is often called red. On the other hand, in the blue water of the Springs, the opposite tendency is seen. Among the neutrals, white often takes on the color of the water in which it is submerged. All of these differences are, of course, in accord with the spectral distribution of light from the target which reaches the eye after being filtered by the water.

Since the appearance of each color is almost always changed toward the ones closest to it on either side in the spectrum, the best solution for correct absolute identification is to use only two colors. One, chosen from the short wavelength portion of the spectrum, green, and one from the long, orange, should never be confused. Black is always correctly identified and can be added to green and orange as a third color. It will, however, be confused with red in clear water and with blue in murky water. White, while highly visible, is too often perceived as having a hue and should not be used where confusion among colors must be avoided.

Any additional colors should be chosen for the particular body of water. For example, blue is perfectly identified in clear water and is a suitable addition there, while yellow and red could be easily discriminated and substituted for orange in murky water.

DISCUSSION

The data are in general agreement with theoretical predictions which can be made concerning visibility through the water. For adequate prediction, we must know (1) the absolute spectral distribution of energy falling on the target after transmission through a given distance d_1 of water, (2) the spectral reflectance of the target in the direction of the observer, (3) the spectral distribution of reflected energy reaching the eye after transmission through the distance d_2 to the eye, (4) the absolute spectral distribution of energy from the water background reaching the eye. From these values, we may calculate the contrast, both brightness and color, to the human eye and predict relative visibilities on the basis of the greatest and least contrast values.³ For simplicity, d_1 and d_2 may be added for the non-fluorescent paint.⁴ However, for the fluorescent paints, the distribution of exciting energy is completely distinct from the emitted energy and a variety of interactions are possible.

It has been pointed out that fluorescent paint has a theoretical advantage over nonfluorescent, since exceptional brightness and saturation are achieved by converting short wavelengths to long. This is particularly true of the oranges where reflectances close to 100% are possible. Thus, it is not surprising to find that fluorescent orange is frequently the most visible color.

In clear water an interesting interaction takes place. At depths where long wavelengths are normally poorly transmitted, the indispensable exciting energy for fluorescence, in the 400–520 m μ range, is well transmitted and should produce good fluorescent oranges. This is in fact true at moderate viewing distances; their appearance is both brilliant and of exceptional color contrast with the blue-green background. In clear water, however, the limits of visibility are pushed to such extreme distances that the orange fluorescent energy may be lost before it reaches the eye. This is clearly seen in Figs. 7–9 where the visibility of fluorescent orange drops dramatically as the viewing distance d_2 is increased from 11 to 16 to 26 m.

While some of the physical measurements necessary for precise calculation of underwater visibilities are rather difficult to obtain *in situ*,⁵ the general picture can

³ S. Q. Duntley, J. Opt. Soc. Am. 53, 214 (1963); J. E. Tyler, Appl. Opt. 3, 582 (1964).

⁴ This addition assumes that the attenuation of daylight in the sea is the same regardless of direction. While not strictly true (see, for example, Jerlov, in Ref. 1, p. 36–42), the assumption is adequate for purposes of this study.

⁵ A suitable instrument recently developed by W. G. Fastie is described in J. E. Tyler, J. Opt. Soc. Am. 55, 800 (1965).

obtained with fairly simple calculations from the relative spectral transmittances. Figures 10 and 11 illustrate this by comparing the chromaticities of several targets calculated in air and after filtering by water.

The changes produced by 1.8 m of Thames River water, in Fig. 10, are all toward the long-wavelength portion of the spectrum, thus accounting for the shifts of perceived colors in this direction. The largest shifts, for the blue and green, represent complete distortions of their normal reflectance values. There is less short-wavelength energy than long for these colors in the Thames and the over-all energy level is very low. The targets are correspondingly difficult to see, easily confused, and often called gray or black.

Transmission through water from the Gulf of Mexico produces chromaticity shifts in the opposite direction; calculations for a depth of 16 m plus the horizontal observing distance of 18 m show that all colors move toward the green portion of the spectrum (Fig. 11). For long-wavelength colors, the elimination of the most important part of the original reflectance curve, as evidenced by the sizable chromaticity shift, results in very low total reflectances and lack of visibility. Also illustrated in this figure is a basic advantage of the fluorescent paints. Since the energy conversion to longer wavelengths does not take place until after the energy has been transmitted through 16 m of water, calculations for fluorescent chromaticity are based upon a 18-m distance through water. The shift from the normal reflectance values is thus not nearly as great as for the nonfluorescent colors.

All of these calculations are based upon transmission

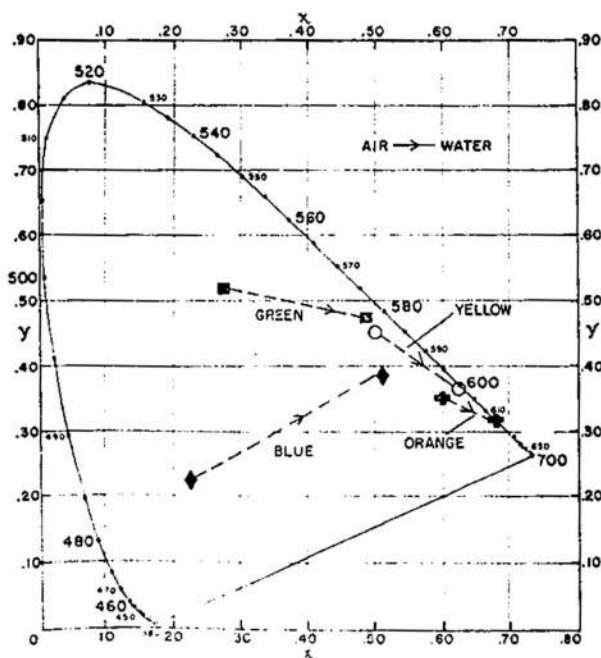


FIG. 10 Changes in chromaticity due to selective transmittance of water from Thames River, Connecticut, at depth of 1.8 m.

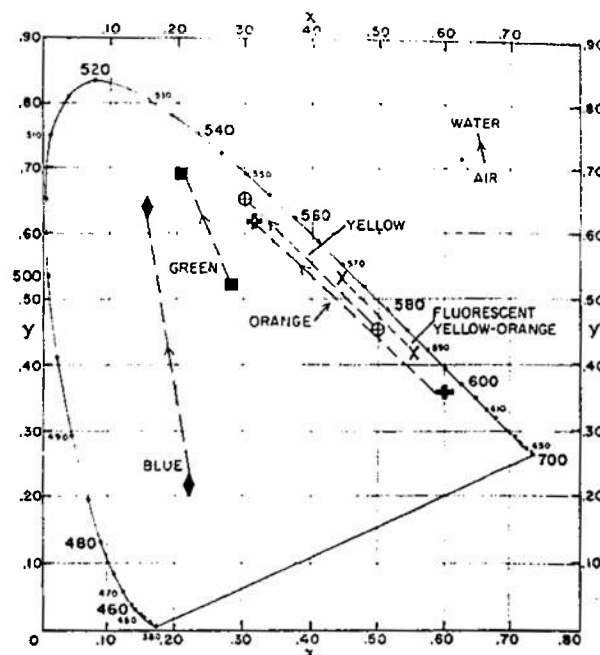


FIG. 11. Changes in chromaticity due to selective transmittance of water from Gulf of Mexico at a depth of 16 m and distance of 18 m.

through that distance and depth which represent the limit of visibility for that body of water. As these distances, either between the observer and the target or the target and the surface, are reduced, with consequent reduction in filtering action of the water, the chromaticities and reflectances will gradually revert toward their values in air.

It has been contended that black is a highly visible color underwater. This was never found in our studies (it was, indeed, the least visible), except in the sense that it was always correctly identified when it was finally perceived. The poor visibility is presumably due to the low contrast provided by black and gray against the dark water background obtained when the subject is at the maximum viewing distance. This conclusion is further supported by the fact that the hues which were not well transmitted by the water (i.e., red in clear water and blue and green in murky) were very difficult to see and were often perceived as black when they were seen. Certain situations can be anticipated in which black could be one of the easiest of non-fluorescent colors to perceive, such as against a white sand or a brightly lighted background. This, however, only serves to emphasize the care with which predictions of underwater visibility should be made.

SUMMARY

I. The colors that are easiest to see underwater at the limits of visibility with natural illumination and a water background are as follows:

(1) For rivers, harbors, and other turbid bodies of water, fluorescent orange is the most visible. Non-

fluorescent colors of good visibility are white, yellow, orange, and red.

(2) For coastal waters of mediocre clarity, fluorescent green and fluorescent orange are superior. White, yellow, and orange are the best non-fluorescent colors.

(3) For clear water, fluorescent greens and white are the best choice. As the clarity of the water is increased, with a consequent increase of viewing distance, the most visible color will change from yellow-green to green to blue-green.

(4) Fluorescent materials are superior to non-fluorescent materials of the same color in all bodies of water. White is the best non-fluorescent material in all bodies of water.

II. The most difficult colors to see at the limits of visibility under natural illumination and a water background are gray and black. Others that have poor visibility are those whose major spectral components are absorbed by the water; i.e., orange and red in clear water and blue and green in murky water.

III. Only a limited number of colors will not be confused with other colors underwater. To avoid confusions, if absolute identification is important, the following combinations are suggested:

(1) Green, orange and black.

(2) Blue, green, orange and black in clear water. (Avoid black and red together.)

(3) Green, yellow, red, and black in murky water. (Avoid blue and black together.)

ACKNOWLEDGMENTS

The authors wish to thank Capt. W. F. Mazzone, MSC, USN, who conducted the experimentation underwater and Michael Greenwood, who served as assistant and subject. We also gratefully acknowledge the help of all the Naval divers, from the Submarine Medical Center and the Naval Mine Defense Laboratory, who served as subjects and without whom the experiment would have been impossible.

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) U.S. NAVAL SUBMARINE MEDICAL CENTER, Submarine Medical Research Laboratory		2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	
		2b. GROUP	
3. REPORT TITLE THE VISIBILITY OF COLORS UNDERWATER			
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Interim report			
5. AUTHOR(S) (First name, middle initial, last name) Jo Ann S. KINNEY, Saul M. LURIA and Donald O. WEITZMAN			
6. REPORT DATE 23 October 1967		7a. TOTAL NO. OF PAGES 8	7b. NO. OF REFS 5
8a. CONTRACT OR GRANT NO. b. PROJECT NO. MF022.01.04-9005.01 c. d.		9a. ORIGINATOR'S REPORT NUMBER(S) SMRL REPORT NUMBER 503 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
10. DISTRIBUTION STATEMENT This document has been approved for public release and sale; its distribution is unlimited.			
11. SUPPLEMENTARY NOTES		12. SPONSORING MILITARY ACTIVITY U.S. Naval Submarine Medical Center Box 600, Naval Submarine Base New London Groton, Connecticut 06340	
13. ABSTRACT The underwater visibility of various colors, both fluorescent and non-fluorescent, was measured in four different bodies of water. The waters were selected to sample the continuum from very murky to clear. SCUBA divers observed with a horizontal path and other subjects on the surface looked down vertically. Fluorescent colors were always more visible than non-fluorescent, but the specific colors that were easiest and most difficult to see depended upon the body of water.			

DD FORM 1473 (PAGE 1)

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Vision Color Oceanography Vision Underwater Color perception in underwater situations Fluorescent vs non-fluorescent materials, visibility of (underwater)						